Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 371–374

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Upstream events and recurrent CIR-accelerated particle events observed by Stereo/SEPT

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Abstract: The Solar Electron and Proton Telescope (SEPT), part of the IMPACT investigation onboard STEREO, is designed to measure energetic electrons from 30 to 400 keV and protons from 60 to 7000 keV. After successful commissioning, SEPT started its scientific observations in mid December 2006. From January through April 2007, the solar activity was very low. Under these extremely quiet conditions, the enhancements of energetic proton fluxes are characterized by series of low energy ($<$ 1 MeV) bursts originating in the Earth magnetosphere or the bow shock (upstream events) and by recurrent, several days long enhancements associated with corotating interaction regions (CIRs). The frequency of upstream events decays with increasing distance to the bow shock with an e-folding distance of 350 R_E. During the observed epoch, three different high speed solar wind streams originating in coronal holes were present producing a recurrent series of energetic proton events. Energy spectra and multi-spacecraft observations of intensity-time profiles during the events are discussed which show delays inconsistent with a co-rotation scenario.

Introduction

The twin observatories of the STEREO mission, launched on October 25, 2006, will perform comprehensive studies of Coronal Mass Ejections (CMEs) directed towards Earth from two vantage points which allow stereoscopic remote observations of CMEs and multi-point in-situ measurements of their interplanetary counterparts (ICMEs). The angle STEREO-A – Sun – STEREO-B increases at a rate of 44 degrees per year. As the observatories separate, larger ICME structures are revealed by the particles and field instruments of the IMPACT investigation.

SEPT Instrument

The Solar Electron and Proton Telescope (SEPT) has two solid state detectors (SSDs) which are operated in anti-coincidence. One SSD looks through an absorption foil and its partner through the air gap of a magnet system. The foil leaves the electron spectrum essentially unchanged but stops protons of energy up to the energy of electrons

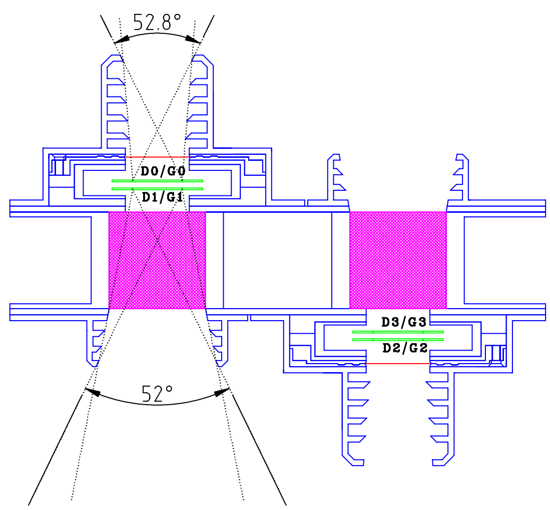

Figure 1: SEPT sensor schematics. Detection elements are silicon detectors (D0…D3, green) with guard rings (G0…G3), Parylene foils (red), and magnetic fields perpendicular to the drawing plane (magenta).

(~400 keV) which penetrate the SSD. The magnet is designed to sweep away electrons below 400 keV, but leaves ions unaffected. Electrons are registered in the energy range 35 – 450 keV with a geometrical factor for the foil telescope of 0.13 cm^2 sr. Protons are registered in the energy range 65 – 6500 keV with a geometrical factor for the magnet telescope of 0.17 cm^2 sr (see Figure 1).

Anisotropy information on the non-spinning spacecraft is acquired by providing two telescopes per spacecraft giving four look directions: SEPT-E observes in the ecliptic plane along the nominal Parker spiral magnetic field direction both forward and backward, SEPT-N/S observes out of the ecliptic plane perpendicular to the magnetic field both North and South. A detailed instrument description is given in [1].

Upstream Events

Upstream events are visible in Figure 4 as short duration spikes (several minutes) above background. We have analyzed 298 events. They show a strong anisotropy from the Earth direction and tend to cluster over the CIR-proton events. The proton differential intensity at the peak ranged from 10 to 10^4 protons/cm^2 s sr MeV. Their frequency of occurrence falls off with increasing distance of STEREO-A from the Earth's bow shock roughly as $x^{-1.6}$ (see Figure 2).

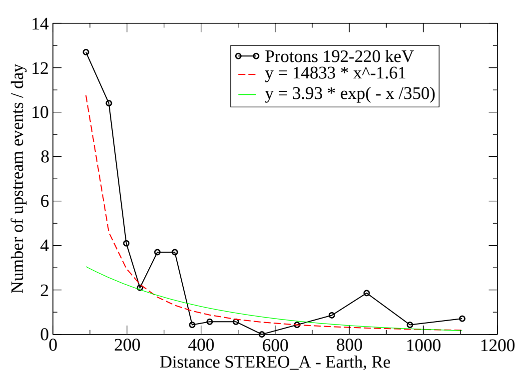

Figure 2: Number of events vs. distance and fits

This is weaker than x^{-2} expected from pure geometry, presumably caused by the interplanetary magnetic field structure. The e-folding distance of 350 R_E is also vastly different from the observations by Ipavich et al. who analyzed upstream events at energies 30-130 keV/Q very close to the bow shock at distances between 0 and 8 R_E which showed an e-folding distance of only 7 R_E [2].

The energy spectra can be represented by power laws, but some events show a peculiar spectral behaviour: They feature line spectra in the range 100 keV to 1 MeV as shown in Figure 3. Similar spectra were reported by Lutsenko et al. [3] and attributed to acceleration in a burst of a strong electrostatic field inside the magnetosphere. Some of these particle packets can leak out of the dayside magnetoshere. The authors could not exclude acceleration at the bow shock, though.

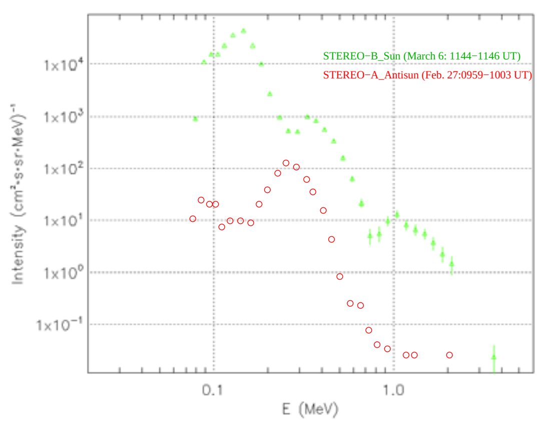

Figure 3: Peculiar energy spectra of upstream events. STEREO-A looking towards Earth/antisun and STEREO-B looking towards Earth/sun.

CIR Events

The period Jan 1 – April 30, 2007 is characterized by very low solar activity. Only three small solar energetic electron events were observed by SEPT on January 23-24. The dominant sources of proton increases are CIRs. The recurrent proton increases (Ai, Bi, Ci in Figure 4) were correlated with three different high speed solar wind streams per solar rotation originating in coronal holes extending near the solar equator. These coronal holes can be seen as dark regions in the soft X-ray images provided by Hinode/XRT and by the open field lines in the solar corona derived using the potential field source surface model (see Figure 4, top). While some coronal holes decay over five rotations (A), others are beginning to develop (C).

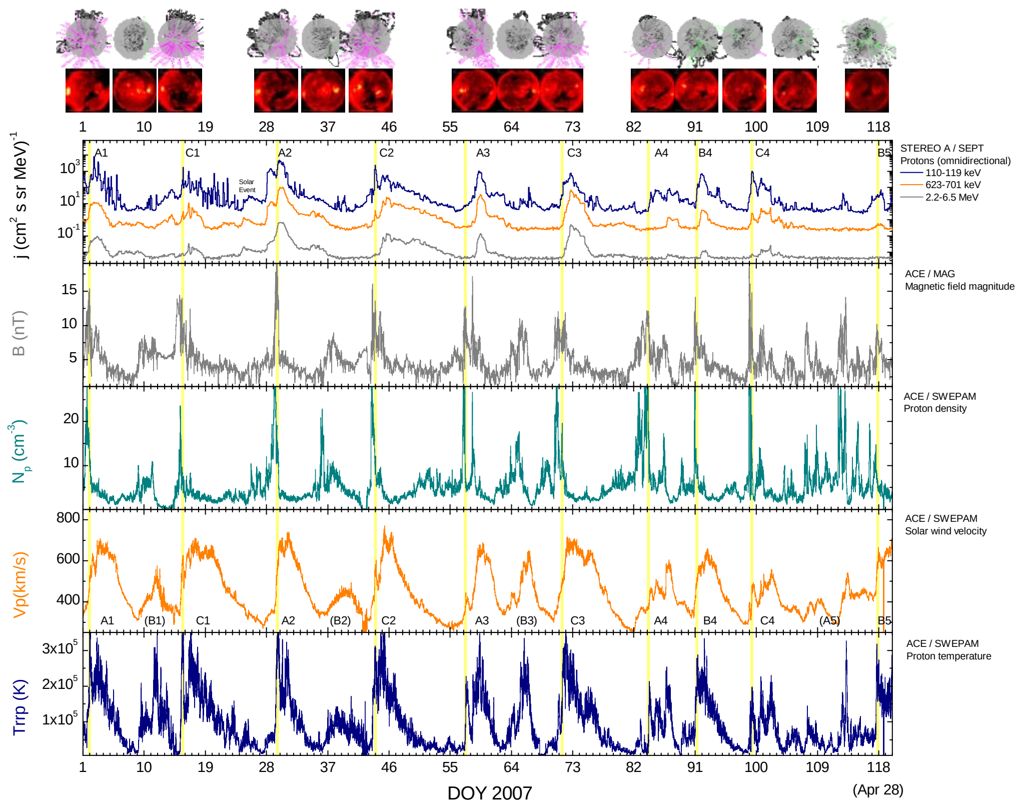

Figure 4: CIR accelerated proton events during 2007

The onsets of the CIR-associated proton increases show lack of velocity dispersion and tend to show progressive spectral hardening, resembling in some cases “inverse velocity dispersion”. Minimum (hardest) spectral indices are reached late in the events, inside the high speed stream, presumably due to the favorable connection to the reverse shock, where the acceleration is stronger. The spectral slope is steeper at higher energies (Figure 5), as predicted by the Fisk and Lee model [4].

STEREO is ideally suited for multispacecraft observations. The time profiles observed by Stereo A and B can be unambiguously compared during periods showing clear features like peaks or sudden drops and increases. Detailed study of these periods reveals that in general the time delay is not consistent with the expected value for a nominal Parker magnetic field line corotating between both spacecraft, already populated with particles originating in the distant CIR shocks beyond 1 AU.

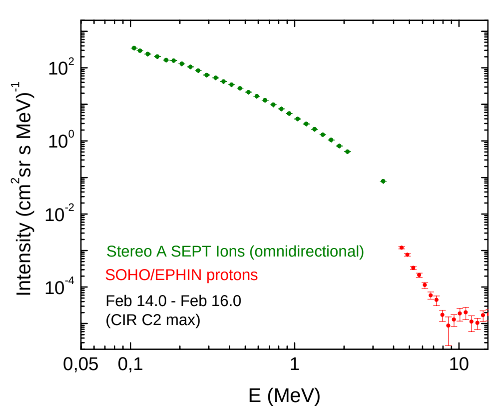

Figure 5: CIR energy spectrum (mostly protons)

The solar wind speed necessary to explain the delays using this idealized co-rotation scenario is unrealistically low (even <250 km/s) for several periods. This could be an indication of strong deviations from the nominal interplanetary magnetic field configuration, even far away from the compression region near the stream interface.

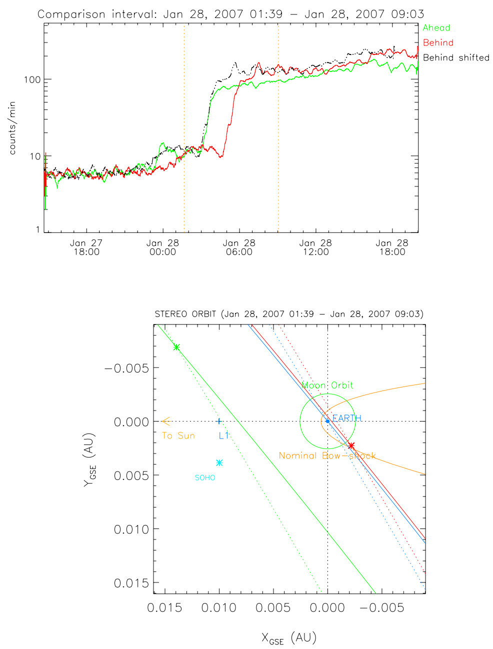

Figure 6: Comparison Stereo A vs. B and spacecraft positions (Ahead = *, Behind = *)

For the event A2 on Jan. 28, omnidirectional proton fluxes in the energy range 496-701 keV are compared in Figure 6 (top) along with spacecraft positions (bottom). Solid lines show ideal IMF lines for a solar wind speed of 329 km/s as measured by ACE. The expected delay from A to B is 1.1 h. The observed delay is 1.85 h. Dashed lines show the ideal IMF lines for V_{sw} = 245 km/s. This low value would be required to explain the 1.85 h delay by corotation.

A rare example of text book corotation is given in Figure 7 which compares omnidirectional proton fluxes in the energy range 101-156 keV for the event on May 19 (not covered by Figure 4). Expected delay from A to B is -7.45 h (i.e. A is delayed), using a solar wind speed of 576 km/s as measured by ACE. Observed delay is -7.4 h. This value is the result of a cross-correlation in the time interval indicated by vertical dashed lines for Ahead.

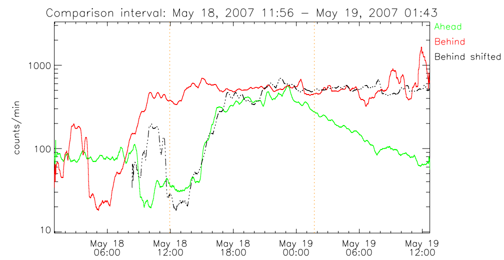

Figure 7: Comparison Stereo A vs. B

Summary

In the extremely quiet period January – April, 2007 the dominant sources of proton increases are CIRs and the Earth's bow shock. Some upstream events show unusual line spectra which are unexplained. Multispacecraft observations of features in CIR time profiles are often inconsistent with a co-rotation scenario. Instead, azimuthal magnetic field lines are required to explain the delays.

Acknowledgements

The authors thank the ACE SWEPAM and MAG instrument teams for providing the ACE data. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. This work was supported by DLR under grant 50 OC 0004.

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